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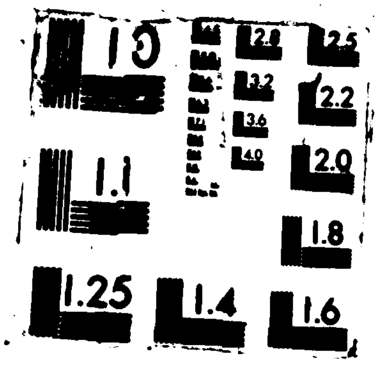

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THE EFFECT OF MOUNTING POSITION ON HOT-FILM WALL SHEAR STRESS SENSORS

LR-6494

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Abstract

Experimental data on the errors introduced in wall shear stress measurements when flush-mounted hot-film sensors are not properly positioned in relation to the test surface are presented. These data lead to the establishment of acceptable tolerance limits when positioning sensors in a calibration facility and also in the subsequent relocation of the sensor to where actual measurements are to be taken. Consideration is given not only to errors in mean values of wall shear stress, but also to RMS and instantaneous values. Results show that the hot-film sensor must be positioned within close tolerances for accurate shear stress measurements. Even though all testing was conducted on a 5 cm diameter pipe with fully developed turbulent flow, results are also applicable to other flows such as that over flat plates and in pipes of larger diameters.

Nomenclature

$\overline{E}$	mean voltage
E_{RMS}	RMS Voltage
l	streamwise length of hot-film
Pr	Prandtl number
dp/dx	pressure drop
R	pipe radius
y	distance from wall
y(5)	height of viscous sublayer at $y^+ = 5$
y^+	Law of the wall distance variable
$\overline{\tau}_w$	mean wall shear stress
$\overline{U}$	mean velocity across pipe
$\overline{U}_{CL}$	mean centerline velocity
U_*	friction velocity
ν	kinematic viscosity

I. Introduction

Some of the earliest investigations using flush-mounted hot-film sensors, similar to the type commercially available today, were in the measurement of mean wall shear stress (skin friction) in the laminar and turbulent regimes of both internal and external flows, Bellhouse & Schultz in 1966(1) and Brown in 1967(2). Subsequent to these studies, many investigators extended the application to numerous areas of experimental fluid mechanics. Some of the more recent studies include the measurement of instantaneous wall shear stress in transient, pulsating flows, Ramaprian and Tu(3), and investigations of the near-wall bursting phenomena associated with turbulent boundary layers, Chambers et al(4).

Throughout that time, others developed calibration procedures for the accurate determination of sensor transfer function (calibration curve). Geremia(5) showed that sensors calibrated in fully developed pipe flows, using differential pressure measurements to determine mean wall shear stress, could be transferred to other flows such as that over a flat plate and still maintain their accuracy. Sandborn(6) developed a method whereby the non-linearity of the sensor transfer function could be accounted for when calibrating sensors in turbulent flows where large fluctuations in wall shear stress were present.

Unfortunately, little information is available on the error induced in the wall shear measurements as a consequence of the probe not being mounted flush with the surface. Bellhouse & Schultz(1) have stated that no errors were introduced in the mean output of flush-mounted hot-film sensors when raised or lowered 0.0762 mm from the flush position in a direction perpendicular to the surface of a flat plate. However, no potentially important characteristics of the flow (such as the height of the viscous sublayer in relation to sensor protrusion into the flow) were given. Since under many operating conditions a linear relationship between sensor heat transfer and $\overline{\tau}_w^{1/3}$ is assumed to hold for laminar flows and turbulent flows when the thermal boundary layer is much thinner than the viscous sublayer (linear portion of velocity profile), correlations with such information are desirable.

This paper presents experimental data on the errors in wall shear stress measurements that result when flush-mounted hot-film sensors are not properly positioned in relation to the surface. These data lead to the establishment of acceptable tolerance limits when positioning sensors in a calibration facility and also in the subsequent relocation of the sensor to where actual measurements are to be taken. Consideration is given not only to errors in mean values of wall shear stress, but also to RMS and instantaneous values.

II. Approach

A commercially available flush-mounted hot-film sensor was calibrated in water at various sensor radial mounting positions relative to the inner wall of a 5 cm diameter cylindrical test section. The sensor, as commercially available, consisted of a quartz-coated 0.127 mm long (streamwise direction) by 1.00 mm wide (spanwise direction) platinum film mounted flush in the end surface of a cylindrical quartz rod encapsulated in a stainless steel cylindrical shell. The overall sensor diameter was 3.175 mm and the sensor surface was smooth and flush to within 0.0254 mm. This particular sensor was chosen since: (1) the diameter is rather large and therefore should have

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greater mounting error than smaller sensors, and (2) the sensor is complete in itself and suitable for immediate use as is.

Tests were conducted in a water flow facility having a 5 cm diameter cylindrical test section and a maximum flow rate of 0.012 m^3/sec. The axial location of the hot-film sensor was in the fully developed flow portion of the test section. All tests were conducted in the turbulent flow regime.

The hot-film sensor was considered to be flush-mounted when the spanwise center of the sensor was flush with the inner wall of the test section as shown in Figure 1. This resulted in the spanwise edges of the sensor surface being recessed into the wall by 0.05 mm. However, since the platinum film itself was only 1.0 mm wide in its spanwise extent, its edges were recessed by only 0.005 mm from the pipe radius. The sensor was located 8 cm upstream of a flanged connection so as to allow easy verification of the flush position. Other sensor positions, whether recessed (into the wall) or protruded (into the flow), were measured externally with a dial indicator using the flush position as a reference. Positioning accuracy was estimated to be $\pm$0.0075 mm.

For each radial position of the hot-film sensor, a calibration was conducted over a substantial flow range or shear stress range. At each calibration flow rate, voltage output from the hot-film anemometer was digitized at a rate of 20 Hz over a 2.5 minute period and stored on a digital computer. Mean and RMS values were subsequently computed.

In addition, mean wall shear stress at each flow rate was obtained by measuring the differential pressure between two pressure taps located 193.2 cm apart in the vicinity of the hot-film sensor. The following relation was applied:

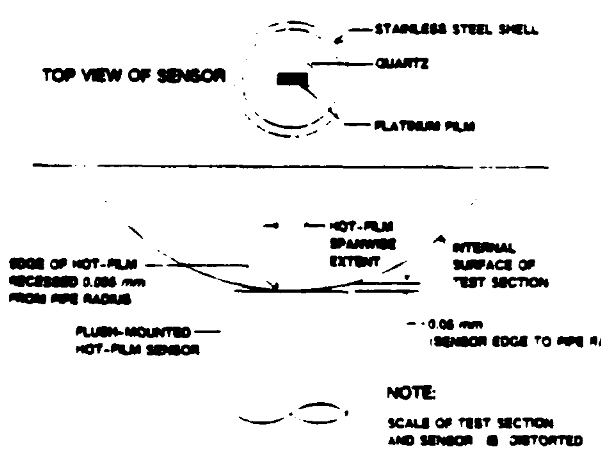

Fig. 1 Flush Mounting Position For Hot-Film Sensor.

$$\overline{\tau}_w = \frac{R}{2}\frac{dp}{dx} \quad . \tag{1}$$

Depending on the actual differential pressure, one of several differential pressure transducers covering various ranges was utilized to obtain increased accuracy. Transducer output was monitored on an integrating voltmeter. Accuracy for the measurement of mean wall shear stress was estimated at $\pm$1.0%.

During several of the calibrations, a Laser Doppler Velocimeter was used to measure centerline velocity in the test section vs wall shear stress. The resulting curve agreed well with that obtained from the Moody chart when the relation[7]

$$\overline{U}_{\mathcal{C}_L} = \overline{U} + 4.07U_* \tag{2}$$

was used to calculate the corresponding centerline velocities for the average cross-sectional velocities of the Moody chart.

III. Results

Tests were conducted with the hot-film sensor mounted in the flush position and at recessed and protruded radial positions of 0.0254, 0.0508, 0.0762, 0.127, and 0.1778 mm from the flush position. Each calibration covered a wall shear stress range of 0.26 to 64 Pascal, corresponding to centerline velocities of 0.240 to 6.70 m/s and centerline Reynolds Numbers from 1.2 X 10^4 to 3.3 X 10^5.

For each data point of the calibrations, values of mean voltage ($\overline{E}$), mean voltage squared ($\overline{E}^2$), and RMS voltage (E_{RMS}) were calculated from the digitized hot-film anemometer data along with calculations of mean wall shear stress from the differential pressure measurements. Calibrations in the flush position were conducted at the beginning and end of the recessed tests and the protruded tests. The resulting good agreement verified that the sensor calibration curve had not changed during the test program as a result of contamination of the hot-film sensor. Temperature variations over the calibrations were negligible.

Data for the recessed mounting tests are shown in Figures 2 and 3 for $\overline{E}^2$ vs $\overline{\tau}_w^{1/3}$ and $E_{RMS}/\overline{E}$ vs $\overline{\tau}_w^{1/3}$, respectively. It should be noted in these and all subsequent figures that an upper scale has been included. This scale shows values of distance from the wall y(5) in mm which corresponds to the point at which the law-of-the wall variable y^+ is equal to 5, the assumed edge of the viscous sub-layer or linear portion of the velocity profile.

Figure 2 shows that the calibration curves for the flush-mounted tests were linear for the relatively large range tested. Brown[2] suggested that this linear relationship would hold in turbulent flows as long as the thermal boundary layer was smaller than the viscous sublayer or

$$\frac{u_* l}{\nu} < 64Pr \tag{3}$$

which is based on a viscous sublayer height of y^+ = 12. For the present set of experiments, this corresponds to

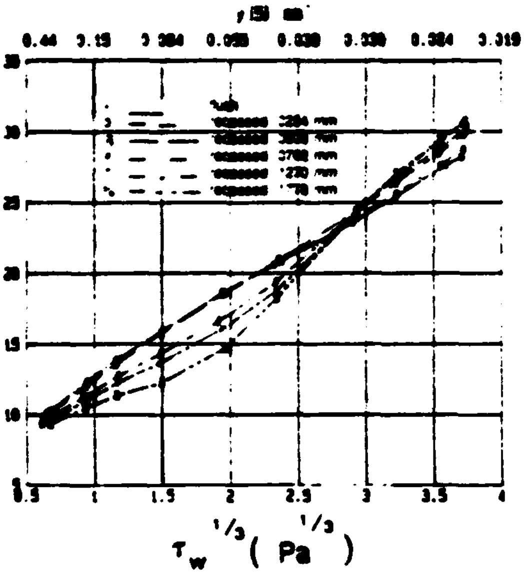

Fig. 2 Calibrations At Recessed Mounting Positions.

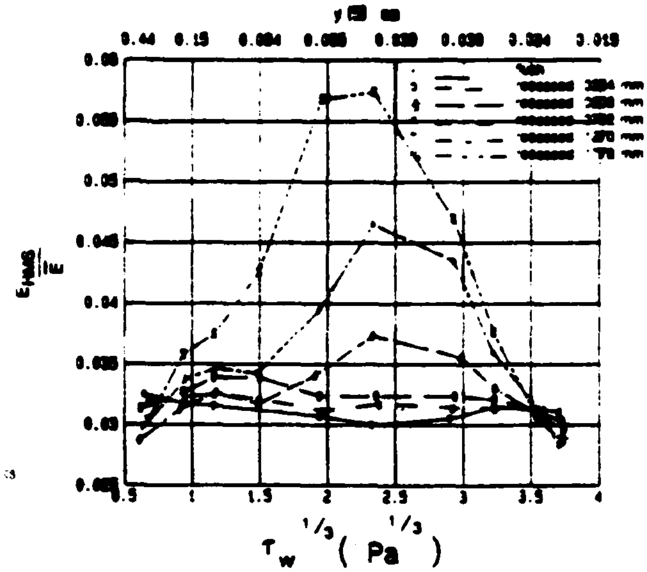

Fig. 3 RMS Values At Recessed Mounting Positions.

$$\bar{\tau}_w^{1/3} < 23\ (Pa)^{1/3}. \qquad (4)$$

The corresponding criterion for a viscous sublayer height of $y^+ = 5$ is

$$\frac{u_* l}{\nu} < 5.6\ Pr \qquad (5)$$

which gives

$$\bar{\tau}_w^{1/3} < 4\ (Pa)^{1/3} \qquad (6)$$

for the present experiments. Since even the more stringent latter criterion is met for the flush-mounted calibrations presented here, the curves are, as expected, linear.

As shown in figures 2 and 3, negligible difference from the flush case was observed as a result of recessing the sensor 0.0254 mm into the wall. When the sensor was recessed 0.0508 mm, negligible error was observed for the lower shear stress range $\bar{\tau}_w^{1/3} < 2.4 Pa^{1/3}$ (y(5) > .042 mm). For larger values of shear stress, the calibration curve remained linear but had an increase in its slope. Errors in $\bar{\tau}_w^{1/3}$ up to 4% and in $\bar{\tau}_w$ of 12% are seen. Very large errors were observed in the three curves for the 0.0762 to 0.1778 mm recessed tests. Errors in $\bar{\tau}_w^{1/3}$ of up to 25% were observed for a recess of 0.0762 mm and up to 50% for a 0.127 mm recess. Corresponding errors in $\bar{\tau}_w$ are 85% and 250%, respectively. In addition, the curves became continuously more non-linear as the recess depth was increased beyond 0.0508 mm. Large non-linearity as evidenced here is considered unacceptable.

Figure 3, $E_{RMS}/\bar{E}$ vs $\bar{\tau}_w^{1/3}$, shows the effect of the disturbances generated by the cavity as the sensor is recessed beyond 0.0508 mm. This disturbance results in an increase of the apparent wall shear stress fluctuations. Differences in $E_{RMS}/\bar{E}$ between the flush position and the 0.0762 mm recess were up to 18%, and they approached 100% for the 0.127 mm recess. It should be noted, however, that the values of $E_{RMS}/\bar{E}$ for the flush position were relatively small (approximately 3%), while those for the worst case, the 0.1778 mm recess, were only 5.7% maximum. Comparing figures 2 and 3, however, it is obvious that these induced fluctuations have a direct influence on the $\bar{E}^2$ vs $\bar{\tau}_w^{1/3}$ curves since errors in these curves follow the change in apparent $E_{RMS}/\bar{E}$.

Sensors recessed up to 0.0508 mm produced negligible increases in apparent wall shear stress fluctuations. Since the calibration curve also did not change when the sensor was recessed 0.0254 mm, it is believed that accurate instantaneous shear stress measurements are realizable for sensors mounted in the flush position to the 0.0254 mm recess position.

Results for the calibrations with the sensor in the protruded positions are compared with the flush calibration in figures 4 and 5. The 0.0254 and 0.0508 protruding positions have nearly identical calibration curves ($\bar{E}^2$ vs $\bar{\tau}_w^{1/3}$) as shown in figure 4. However, values of $\bar{\tau}_w^{1/3}$ deviate from the curve for the flush position by approximately 10%, which also corresponds to a 30% error in $\bar{\tau}_w$. It is interesting to note that the curve for the 0.0508 mm protrusion remains fairly linear even for the smallest y(5) value of 0.021. This linear relationship may not hold, however, for other than fully developed flows.

Sensors protruded from 0.0762 mm to 0.1778 mm have calibration curves that deviate from that for the flush position by up to 15% in $\bar{\tau}_w^{1/3}$ and 55% in $\bar{\tau}_w^{1/3}$ All curves in figure 4 are reasonably linear except for the 0.1778 mm protruded curve which tends to be non-linear at the higher wall shear stress values. The 0.1778 mm protruded curve

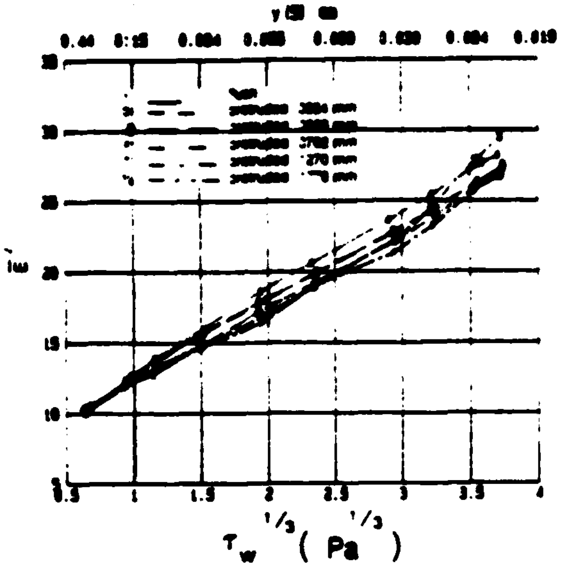

Fig 4. Calibrations At Protruded Mounting Positions.

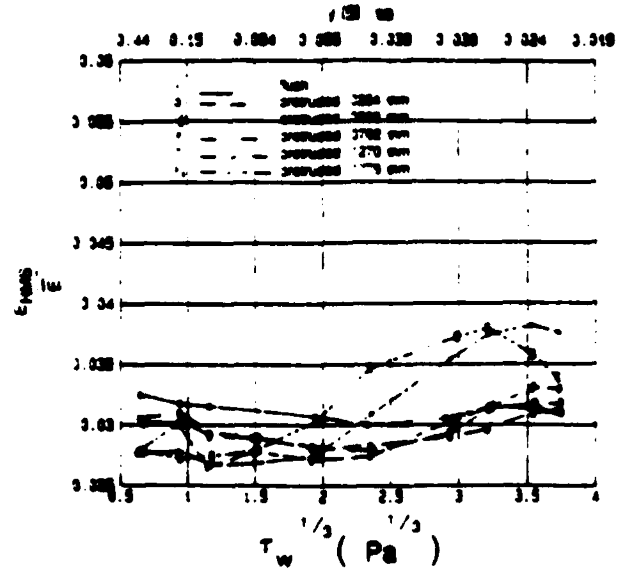

Fig 5. RMS Values At Protruded Mounting Positions.

becomes non-linear at a y(5) value of 0.030 mm, which is one-sixth the height of the protruded sensor. Apparently, the linear relationship between sensor heat transfer and $\bar{\tau}_w^{1/3}$ extends well beyond the viscous sublayer whether based on $y^+ = 5$ or $y^+ = 12$ at least for fully developed pipe flow. According to the above results for the 0.1778 mm protruded case, the curve for the 0.1270 mm protruded sensor should become non-linear at approximately y(5) equal to 0.021; however, this is beyond the end of the curve.

As can be seen in figure 5, differences in $E_{RMS}/\bar{E}$ between the 0.0254 and 0.0508 mm protruded results were negligible over the complete calibration range. For a large portion of the range, $E_{RMS}/\bar{E}$ for these two tests was approximately 2.8% as compared to approximately 3.1% for the flush case. This 10% difference is negligible, however, when considering the low values of $E_{RMS}/\bar{E}$ over the complete range. The 0.762, 0.127, and 0.1778 mm protruded cases had $E_{RMS}/\bar{E}$ values that deviated over a large portion of the range with differences as high as 15% from the flush position. Again, however, the values of $E_{RMS}/\bar{E}$ for all curves range from 2.6% to 3.8%, which are all rather small values. The value of $E_{RMS}/\bar{E}$ for each of the curves with the three largest protrusions starts to increase sharply when the viscous sublayer height at $y^+ = 5$ reduces to approximately one-half the protrusion height. If the viscous sublayer height is taken at $y^+ = 12$, as suggested by Brown[2], then the curves become non-linear at the point where the viscous sublayer height is comparable to sensor protrusion height.

Unfortunately, energy spectra were not obtained for these tests. If they were, some information relative to the turbulence generated either by the cavity or the protruded sensor could have been obtained. For instance, the frequency information could be used to determine whether the turbulence could indeed have been generated by the cavity and also provide some information on its effect on measured burst frequency.

IV. Conclusion

Flush-mounted hot-film wall shear stress sensors can be used to accurately measure mean, RMS, and instantaneous wall shear stress when reasonable care is taken in positioning the sensor flush with the wall. The optimum flush-mounted position is with the spanwise center of the sensor being flush with the pipe wall, which results in the spanwise edges of the sensor being recessed. Since no portion of the sensor protrudes into the flow and, as shown, the sensor calibration curve remains linear even for very small values of viscous sublayer height, the sensor can be used to measure wall shear stress for flows having other than fully developed profiles. The effect of the recessed edges of the sensor is negligible on the $E_{RMS}/\bar{E}$ values and consequently also on the instantaneous wall shear stress.

If the sensor is calibrated in one facility and moved to another, the tolerance in positioning the sensor is relatively small, ranging from the flush position to the 0.0254 mm recessed position. Should the sensor be calibrated in-situ and should the flow conditions (velocity profile, viscous sublayer height, etc.) remain similar between calibration and future tests, then the sensor can be positioned between the 0.0254 mm recessed and the 0.0762 mm protruded position and still have a repeatable linear calibration curve. However, if the sensor is protruded substantially into the viscous sublayer, then E_{RMS} and instantaneous wall shear stress measurements could have large errors.

These conclusions are believed valid, although conservative, for measurements on flat plates and on internal surfaces with a pipe diameter equal to or greater than 5 cm and for wall shear sensors up to 3.175 mm in diameter.

Acknowledgements

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